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Augmented Reality in a Simulated Tower Environment: Effect of Field of View on Aircraft Detection

Stephen R. Ellis, Bernard D. Adelstein, Ronald J. Reisman
Ames Research Center, Moffett Field, California

Joelle R. Schmidt-Ott, Jonathan Gips
San Jose State University Foundation, San Jose, California

Jimmy Krozel
Seagull Technologies

National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

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1. Introduction

On February 1, 1991, a USAir B-737 collided with a Skywest Metro at the Los Angeles airport. The accident occurred at night while the Metro was awaiting takeoff clearance on a runway. The Metro had taxied into position at an intersection some distance down the runway. The B-737 had been cleared to land on the same runway. The tower controller could not see the Metro in the lights of the runway and, because a flight strip for the Skywest was not at the controller's position, he forgot that it was awaiting takeoff. The National Transportation Safety Board cited the lack of proper management in the tower facility, from the perspective of both oversight and policy direction, and failure of appropriate coordination in following procedures in the tower as contributory causes of the collusion. The controller was very busy and did not have adequate backup, nor was the surface radar available for monitoring the aircraft on the airport (Wickens et al., 1997).

The stated safe orderly and expeditious goals for the air traffic control system is to accomplish the safe, efficient flow of traffic from origin to destination. The goals of safety and efficiency are to some extent opposing. The pressure for safety, especially from the traveling community is enormous and understandable, yet to ensure total safety we would not fly at all. In fact, to ensure a greater safety level than we have today, separation between aircraft would have to be greater, than is currently the practice. However, this would reduce the efficiency.

In an attempt to avoid the trade-off between safety and efficiency this study focuses on a new technology of displaying radar data to operators via see through HMD and examines the impact of varied displayed fields of view (FOV) with the purpose of establishing design recommendations for equipment of this kind in Air Traffic Control (ATC) towers.

The FOV is one of the most prominent human factors issues for a useful HMD system. While intuition suggests that a restriction in the FOV should decrease the user's performance, the extent of degradation varies substantially with tasks. Because of the very wide field of regard required for operators in the tower, the appropriate FOV for this specific application needs to be evaluated. Therefore subjects' ability to detect aircraft maneuvering and landing were tested in an ATC Tower simulation for the Dallas Ft. Worth International airport. Subjects monitored traffic patterns as if from the airport's western control tower. Two experiments were conducted. The effects on aircraft detection performance of three different FOVs (14°, 28° and 47°) were tested in order to provide a parameter estimation for the needed FOV. In the second experiment, separate groups were presented with either the 100% or 46% overlap to determine if partial overlap may be a feasible technique to use to develop augmented reality displays for the tower application.

2. Some Theoretical and Empirical Background

In the following an up-to-date survey of work creating augmented realities is presented along with a compilation of empirical approaches toward developing suitable techniques.

2.1 Augmented Reality (AR)

The topic of Augmented Reality (AR) appears in the human factors' literature with increasing frequency, usually in conjunction with the discussion of the more familiar subject of Virtual Environments (VE) more commonly called Virtual Reality (VR). Several years ago these so called "virtual reality" media caught the international public imagination as a qualitatively new human-machine interface (Pollack, 1989; D'Arcy, 1990; Stewart, 1991; Brehde, 1991). But they, in fact, arose from continuous development in several technical and non-technical areas during the past 25 years (Ellis, 1990, 1996; Brooks, 1988; Kalawsky, 1993).

However, little consensus on precise definitions of either VR or AR can be reported. VR, for example, is used to refer to systems ranging from totally immersive computer generated virtual environments, to interactive desktop computer graphic applications, to text-only "Adventure" style computer games (Milgram et al., 1994, 1995). In general VE or VR completely immerse a user inside a synthetic environment. While immersed, the user obviously cannot see the real world around him.

AR allows the user to see the real world with virtual objects superimposed upon or composited with the real word. Therefore, AR supplements reality, rather than replacing it (Azuma, 1997). Milgram and Colquhoun (1999) describe two classes of definitions for Augmented Reality distinguished from each other in their terrain of breadth: First, in the case of display systems comprising some kind of head mounted display (HMD) or head-up display (HUD), the viewer has a direct "see-through" view of the real world, either optically or via video mixing, upon which is superimposed computer generated images (CGIs).

A second, broader class of definitions in the literature relaxes the constraint of needing the equivalent of a HMD and covers "any case in which an otherwise real environment is 'augmented' by means of virtual (computer graphic) objects." This definition includes large screen and monitor based displays.

Milgram and Colquhoun (1999) add a third, even broader class of AR displays than has been proposed in the literature. It encompasses those cases involving any mixture of real and virtual environments. Consistent with their interpretation, Azuma (1995), in an earlier survey referred to AR as "a variation on Virtual Environments that combines virtual and real." Azuma (1997) later refined this definition and defined AR as system that the following three characteristics: 1) Combining real and virtual, 2) Interactive in real time, and 3) Spatially registered in three dimensions (3-D). With this definition he avoids limiting AR to specific technologies such as HMDs.

Milgram and Colquhoun (1999) have since developed a new set of definitions for AR, which are presented in the following chapter.

2.2 The helmet mounted display (HMD)

2.2.1 Various HMD systems

The head-mounted display (HMD) is a critical link in virtual environment and visually coupled systems. HMDs represent a group of viewing systems. The concept of these devices is to provide symbolic or pictorial information by introducing into the user's visual pathway a virtual image the user can observe regardless of the direction of gaze (Velger, 1998). This is achieved by using a display mounted on the head together with continuous measurements of the head position.

Two kinds of head mounted displays can be distinguished: Video see-through and optical see-through systems. Video see-through systems combine synthetic images with the real user's surroundings by combining two video streams, one usually coming from a computer, the other one coming from a video camera that is mounted to the user's head. Optical see-through systems combine the real and synthetic imagery via some optical merging array like a "half-silvered" mirror (Fuchs & Ackerman, 1999).

In its simplest form, an HMD consists of an image source and accommodative optics in head mount. The HMD can then become more elaborate in several ways. There may be one or two display channels. These channels may display graphics and symbology with or without video overlay. They may be viewed directly and occlude external vision for a fully immersing experience, or they may use a semitransparent combiner with see-through to the outside world. In this "augmented reality" mode, the HMD may overlay symbology or other information onto the real world view (Melzer & Moffitt, 1997). In this study an optical see-through system will be used. Figure 2 shows a conceptual diagram for such HMD.

The HMD is part of a larger system that can include an image generator, a head tracker, as well as audio and manual input devices. The image generator may be a sophisticated image rendering engine or a personal computer. A tracker, which communicates the location and orientation of the user's head to the image generator, immerses the user in a virtual environment. This immersion is often enhanced by using a joystick or a 3-D mouse, or instrumented glove to manipulate virtual objects (Melzer & Moffitt, 1997).

The information displayed on the HMD can vary from simple unchanging symbology, through more complex changing information like numerically presented speed notation, to complex graphic imagery superimposed on a video image obtained from a sensor.

HMDs can be constructed in one of three forms:
(1) Monocular, in which the display is viewed only by a single eye (left or right)
(2) Biocular, in which the same image is presented for both eyes
(3) Binocular, in which two distinct images are presented independently to the right and left eyes.

Biocular displays use one image source and either a single set or double set of optics and thus have larger weight than

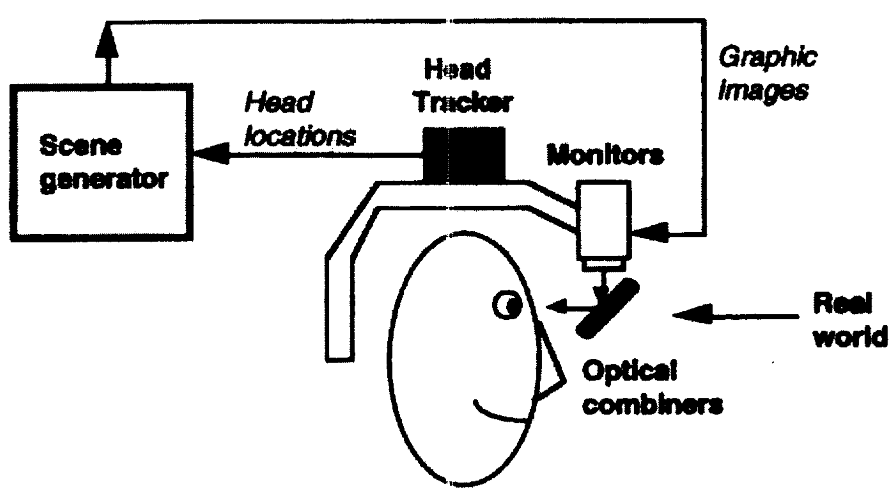

Figure 2. Optical see-through HMD conceptual diagram (adapted from Azuma, 2001).

monocular systems, which use a single image source and a single set of optics. Binocular displays employ two image sources and two sets of optics and thus have even greater weight and volume. There are many advantages to binocular displays. Beyond their capability to provide stereoscopic cues and depth perception, they can be used to extend the field of view (FOV) by presenting partially overlapped images (Velger, 1998).

2.2.3 Human factors in the design of HMDs

The ultimate goal for any head-mounted display system is to enable the user to achieve task objectives to an acceptable level and with a reasonable expenditure of effort (Eggleston, 1997). This implies that the relation between system properties and specific aspects of user performance must be recognized to make successful design suggestions for HMDs.

It is often not easy to discern the relation between a detailed design issue and its impact on human performance. As a result, the designer may tend to concentrate on technology factors during design problem solving. A "human-factored" approach for the construction of a "human-centered" HMD system favors the perspective of the user to support his roles and tasks (Riley, 1995; Rouse, 1991). This approach may differ from a purely engineering approach, where technology comes first.

A fundamental problem in designing HMDs is the lack of specifications and accepted numerical values that bound the limits of human performance. Besides a small set of commonly held rules of thumb, the human factors database for HMD design is simply inadequate (Melzer & Moffitt, 1997).

There are four fundamental areas that must be satisfied in the HMD design or selection process: visual, physical, environmental and interface requirements. Some of the challenging hardware requirements for HMD designs include the need for wide-field-of-view and high-resolution imagery, the goal to maintain image alignment of a complex electro-optical system, the need to fit a range of head shapes and sizes and the attempt to minimize head-supported weight for comfort and safety.

Properly designed HMDs can fit comfortably and be worn for several hours. Improperly designed, an HMD can quickly strain the user's eyes, neck, or sense of balance with symptoms that can last for several hours (Melzer & Moffitt, 1997). Negative side effects can result partially from poor HMD design and partially from an incomplete understanding of how humans and HMDs interact (Peli, 1990, 1995). Side effects range from cyber sickness (a form of motion sickness) (Regan, 1993; Regan & Price, 1994; Kennedy et al., 1993), to visual stress (Miyashita & Uchida, 1990), to dissociation of the accommodation-vergence response (Mon-Williams, Wann & Rushton, 1993; Woepking, 1995).

2.3 Field of view (FOV)

One of the important human factors design issues in regards to HMDs is to establish recommendations of the required binocular field of view (FOV) for specific tasks.

2.3.1 Definition of FOV

The FOV can be defined as the angular extent of a display or aperture with regard to a user's eye point, usually expressed in degrees of visual angle. The related technical term , "visual field", is a mapping of the perimeter of visibility of the eyes.

The instantaneous field of view is defined as the sensor's field of view without any movement, like eye- or head-movements. For humans, the instantaneous monocular FOV is about 160° in the horizontal direction and about 120° in the vertical direction. The FOV is wider on the temporal side (about 100°) than it is on the nasal side (about 60°) because the nose blocks part of the FOV. The instantaneous binocular field of view for humans is about 200° of visual angle in the horizontal direction (figure 3). Although both horizontal and vertical FOVs matter, the horizontal FOV is often emphasized because it is considered more important (Thorpe Davis, 1997).

2.3.2 FOV considerations and design trade-offs in HMDs

No existing HMD achieves the wide field of view (FOV) of the human visual system operating in a real environment. Intuition, and the available evidence, would lead to the expectation that decreasing the FOV size to less than the normal would result in a performance loss. Specifying the FOV for a HMD is a complex task. A number of interdependent parameters need to be taken into consideration for a cost/benefit analysis using data on the effects of different parameters on performance.

One of the most pressing challenges facing designers and developers of HMDs is to simultaneously provide the user with a wide FOV and good spatial resolution.

In order to achieve a wider FOV with a fixed number of pixels, the pixel was magnified and therefore the spatial resolution iwas decreased. Helmet weight is another consideration in the design process, since increasing the FOV usually involves some weight increase due to larger optical elements.

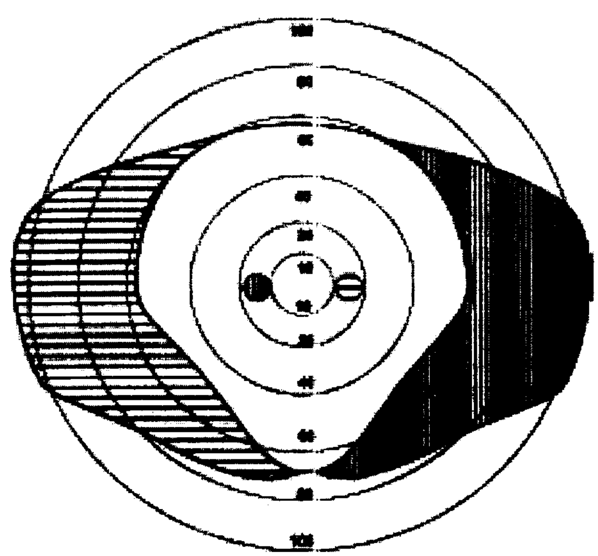

Figure 3. The visual field of the normal human. The vertically shaded area is the right-eye monocular visual field, while the horizontally shaded area is the left-eye monocular visual field. The white central area is the binocular visual field (adapted from Velger, 1998). The concentric rings mark radii of angular distances in degrees from the visual axis of the eye. The small circular regions near the center show the locations of the left and right eyes' blind spots.

Wells and Venturio (1990) state that the following holds true: Increasing the FOV size, increasing the image resolution and decreasing the HMD weight may all be expected to improve performance. However, increasing the FOV size by increasing optical magnification increases the HMD weight and decreases image resolution. Both of these factors affect comfort and performance.

A HMD with wide field of view and high resolution is very desirable for most applications. But using traditional optical methods as described above, an HMD cannot have both simultaneously because these two display attributes are linked by the focal length of the collimating optics.

Melzer (1998) reviews four techniques to increase the FOV while maintaining image resolution:

d. High resolution area of interest: This technique presents a high-resolution, head tracked central image with small FOV superimposed over a lower resolution peripheral vision background.

(2) Dichoptic area of interest: A low resolution, wide field channel is displayed to one of the user's eyes while a much higher resolution, but smaller FOV channel is displayed to the user's other eye. It is similar to the high resolution of interest approach with the benefit that it requires only two video channels and no tracker.

e. Optical tiling: In this approach a series of small FOV, high-resolution displays are arranged in a mosaic pattern, similar to a video wall. Overlapping the optical fields minimizes the seams between the adjacent tiles.

(4) Partial binocular overlap: The FOV is enlarged by physically canting the optical relays inward or outward, leaving an area in the center for binocular viewing that is flanked by unpaired monocular regions. This approach will be discussed in more detail in chapter 2.3.4.

However, exactly how large a field of view is needed for specific applications requires investigations of the particular cases.

2.3.3 FOV size and task complexity

Two related questions about the necessary size of FOVs are (1) What is the minimum FOV necessary for acceptable performance? and (2) What effects do smaller FOVs have on perception and performance?

Alfano and Michel (1990) reported that each restriction of the normal field of view to 9°, 14°, 22°, or 60° resulted in perceptual and performance decrements of visuomotor activities. In addition, bodily discomfort, dizziness, unsteadiness and disorientation, were reported as the subjects moved around with restricted fields of view, although wide FOVs can increase simulator sickness as well (Padmos & Milders, 1992). These findings have led to interest in exploring possible simulation induced side effects in the ATC application with the Simulation Sickness Questionnaire (SSQ) (Kennedy, 1993). The SSQ will be used as an exploratory instrument in this study.

Sandor and Leger (1991) reported significantly reduced visuo-manual tracking performance with a restricted FOV of 20°. In the case of see-through HMD displays that included applications involving symbology and alphanumerics, good foveal resolution is needed and the minimum monocular FOV is 15 to 30 degrees (Wells & Haas, 1992).

Literature reveals that field of view requirements FOV is depend on task complexity. Wells and Venturio (1990) reported that increases in task complexity required an increase in the FOV. In a task of medium complexity performance was significantly different in 20° and 45° FOV conditions. Eggleston et al. (1997) found a pronounced FOV effect at moderate task difficulty, however, a diminished effect when difficulty increased to a higher level.

At this point no general FOV recommendations for different task complexities are available to HMD designers, and the optimal or minimal FOV for HMDs remains an unresolved issue. For specific tasks, like pilot training in simulators, recent research has been conducted to estimate the necessary FOV (Schiefele, Doerr., Kelz, & Schmidt-Winkel 1999). A similar study was done for rotorcraft pilots (Kasper et al., 1997; Szoboszlay et al. 1995).

Other FOV research studies investigated the role of FOV on the sense of presence and orientation in simulated environments. A wide FOV display can produce better orientation within the environment and a stronger sense of self-motion (Padmos & Milders, 1992). Hatada, Sakata and Kusaka (1980) observed that the "sensation of reality" increased in proportion to the viewing angle but there was little added benefit when the viewing angle exceeded 60°. McCreary and Williges (1998) found significant increases of spatial knowledge with increasing FOV. Such findings were questioned by Johnson and Stewart (1999) with their data revealing that the type of visual display made no difference in the amount learned and in the reported experience of presence.

Too small a field increases the number of head movements the user must make to determine where things are located and interferes with situation awareness.

Moreover, peripheral vision can help in ego-orientation, locomotion and reaching performance (Dichgans, 1977, cited in Alfano and Michel, 1990). A wide FOV display can produce better orientation within the environment and a stronger sense of self motion (Padmos & Milders, 1992).

This literature review reveals the significant impact of FOV size on parameters like performance, physical well-being, and situational awareness. Consequently, HMD designers may be asked to evaluate design issues in regards to available technology, specific task requirements and user as well.

The limitations of the size of field of view in available HMDs using the full overlap display mode, where the entire FOV is binocular, suggest the consideration of methods like partial binocular overlap displays to enlarge the FOV.

2.3.4 Increasing the FOV by using binocular overlap

In humans or other higher mammals, both eyes share a large portion of the visual field. Binocular vision is defined as the neural and psychological interaction of the two eyes pertaining to this region of overlap. Although a single eye can function well alone, human vision is fundamentally binocular. The predominant feature of binocular vision is that of stereopsis, a function that transforms those differences between the monocular images, which are due to differences in angle of regard, into a vivid impression of solid three-dimensional space.

Melzer (1998) discusses partial binocular overlap as a method to increase the field of view while maintaining image resolution and using the same optics. With a partial binocular overlap the user would see a central binocular image flanked by two monocular images (figure 4). Partial binocular overlap enlarges the FOV by

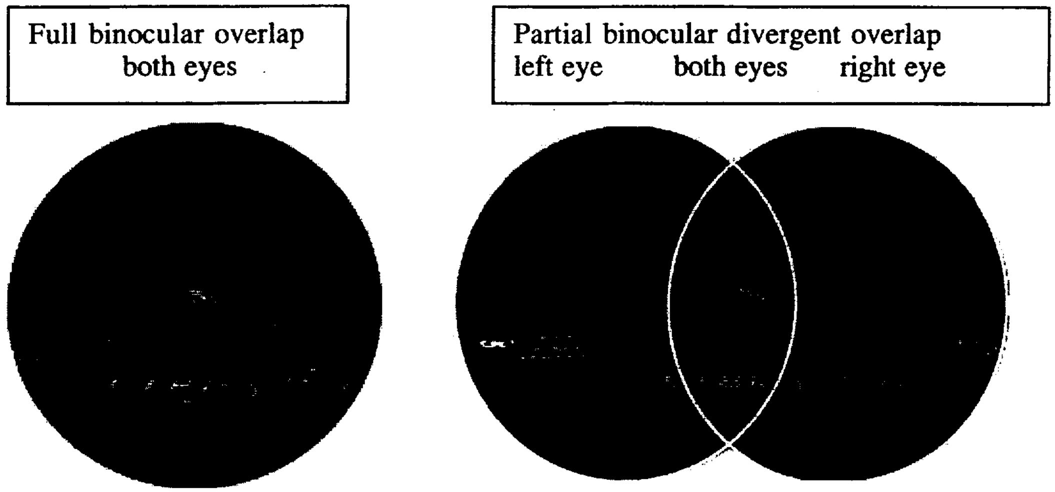

Figure 4. Full binocular overlap versus partial binocular overlap (divergent) as used in the ATC simulation (white lines indicate the areas where luning occurs).

physically canting the optical relays inward or outward. Inward canting is referred to as convergent overlap; outward canting is referred to as divergent overlap (figure 5).

Melzer and Moffitt (1989) evaluated divergent and convergent partial binocular overlap displays for reducing edge effects. "Luning" is a psycho-physical phenomenon observed in partial overlap displays associated with binocular rivalry from viewing dissimilar imagery. The term luning originated from the crescent-shaped edges of the circular image sources. The concern has been that luning may cause image fragmentation, loss of visual sensitivity, eyestrain and place the burden of additional workload on the user. Melzer and Moffitt (1991) attempted to explain the difference in the degree of luning observed between convergent and divergent displays with an ecological vision model. Convergent overlap was theorized to induce less luning because it was more "ecologically valid" than the divergent case. There was less luning found in convergent displays where the monoculars were tilted inwards to create the partial overlap.

Klymenko et al. (1994) describe luning as a subjective darkening in the monocular regions of the FOV, which can in some cases cause fragmentation of the FOV into three regions. They tested a number of display factors on luning: 1) convergent versus divergent, 2) display luminance level, 3) the presence of either black or white contours or no contours on the binocular overlap border, and 4) lowering or raising the luminance of the monocular side regions relative to the binocular overlap region. The divergent display mode systematically induced more luning than the convergent display mode under the null contour condition. Klymenko et al. (1994) also investigated the effect of display modes (full overlap, convergent and divergent mode) on visual sensitivity across the FOV. Four positions in the FOV were tested: monocular, binocular, each of which could be near or distant from binocular overlap border. The results indicated that for all spatial and temporal frequencies, the probes had higher thresholds in both of the partial overlap display modes, where the probes were monocular, compared to the full overlap display mode, where the probes where binocular. Increases in threshold for the divergent compared to convergent displays were found.

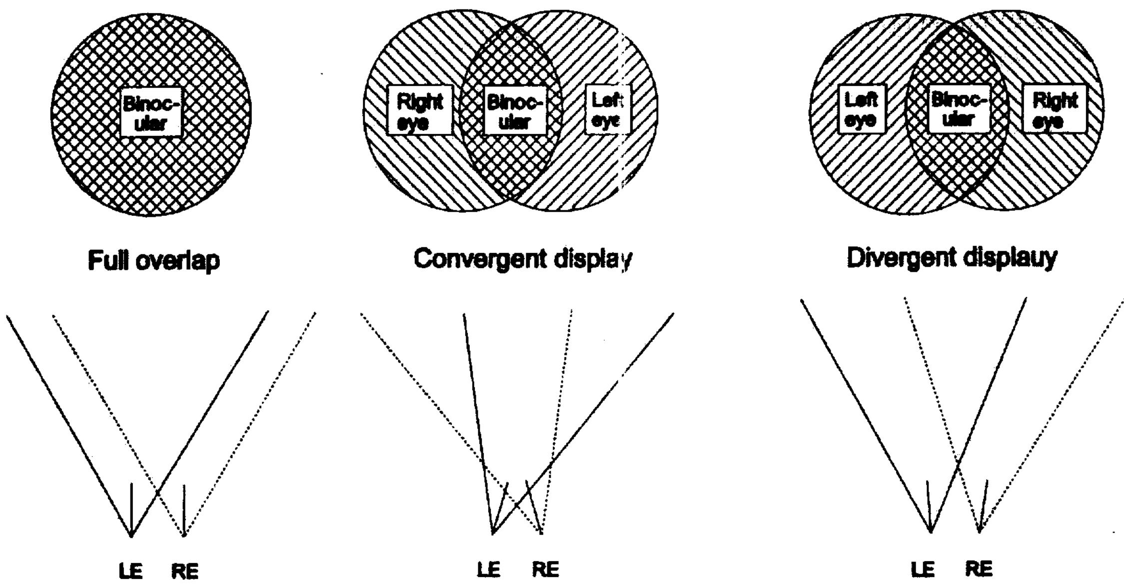

Figure 5. Various configurations of binocular overlap (divergent, full and convergent).

Diverse opinions are reported in studies that attempted to identify the minimum amount of overlap required. Kruk and Longridge (1984) found no performance degradation in target detection, or tracking for a binocular overlap of 25° and 45°. There was a degradation of motion detection at the edges of the 25° overlap.

Landau (1990) hypothesized that smaller overlap percentages will place the problematic edges (luning) closer to the observer's central field of view where they become more detectable and distracting. They found that the 35% or 17° overlap used in her recognition study produced degraded performance, while the 80% and 100% overlap conditions did not reveal differences in accuracy or temporal performance. Behaviors previously associated with small overlap were also noted in this study: the tendency for head movement, variations in brightness and the tendency for binocular rivalry or suppression. It is true that as the amount of overlap is decreased, image distortion resulting from the edge of the optics begins to be centered in the field of vision and small overlap areas are not recommended (Landau, 1990).

In their driving study, Tsou et al. (1991) evaluated the effect of various configurations and amounts of binocular overlap on performance using a 60° FOV. They reported that subjects did not comment on any specifics regarding partial overlap conditions. No consistent differences between divergent and convergent overlap in terms of course time, error, head velocity or movement were found by Tsou et al. (1991). In contrast to ordinary binocular vision and the conditions in a divergent display, in a convergent the right eye will see more of the left (nasal) visual field and the left eye will see more of the right (nasal) visual field (See Figure 5); Consequently, if a target is moving from right to left, the left eye will detect the target before the right eye picks it up. This may cause confusion if the convergent panoramic display is not totally fused by the two eyes. Tsou, et al.

did not test this possibility directly in their study. Their study revealed differences in FOV, but no significant effects between binocular overlap levels and configurations. These authors tentatively suggest that some tradeoffs of binocular vision for a larger overall display FOV are acceptable.

2.4 The air traffic control (ATC) tower application

In many respects augmented reality displays, like that used for this experiment, function in a manner similar to cockpit head-up displays (HUD) in aircraft, which provide status and spatially conformal information, e.g. the runway symbol, to pilots. Much of the benefit of using a HUD has been attributed to the better information integration provided by the HUD symbology which collects widely distinguished spatial and other status information in one place (Weintraub & Ensing, 1992). Accordingly, since congestion at commercial airports has focused attention on new technologies that could improve airport efficiency, interest has developed in transferring some of display benefits provided to pilots by HUDs to air traffic controllers in airport towers.

The proposal for HUD-like displays in towers, in fact, is not entirely new, being suggested by Lloyd Hitchcock in the late 1980's (Weintraub & Ensing, 1992, p.144). Displays like HMDs could be introduced to the towers and would be expected to provide controllers with status information by text fields showing barometer settings, wind conditions, and runway and gate assignments. They could also superimpose aircraft identifications onto arriving and departing aircraft. Additionally, HMDs could provide the tower controllers with a kind of "X-ray vision" that would conceivably allow them to continue airport operation in weather conditions that would otherwise close the airport or at least significantly reduce its capacity.

The control tasks within the tower are usually divided between the ground controller who controls taxing aircraft on the ground and the local area controller who controls aircraft just before takeoff and just before landing, both of them generally being located in a window room on top of the tower. Most local controllers initially receive flight and identification information about aircraft on paper strips, so called "flight strips" and need to detect the specific aircraft outside of the window before a clearance for landing or take off can be given. Flight strips are physical representations of each aircraft, which are computer generated at the time the flight plan is filed and represent a visible reminder of an aircraft's status in the sequence of taxi-takeoff (for departure) and landing-taxi (for arrival). As they are physically moved around the controller's workstation, they are a reminder of what each represented aircraft is doing and thereby generally helping to maintain the big picture of who is where (Wickens et al., 1997).

Because all aircraft are nominally within sight of the controllers in the tower, the most important resources at their disposal are their eyes, coupled with a voice communication link. In fact, they are generally required by law to see all aircraft they control. The challenge is to always know who they are looking at. This is not a trivial task at a busy airport.

As cited above, literature reveals the close relation of task complexity and FOV on performance (Wells & Venturio, 1990; Eggleston, 1997). While intuition clearly suggests that restriction of the FOV should degrade performance, the extent of this degradation varies substantially with tasks. Local controllers in a tower can require a field of regard on the order of 180° for their immediate task, but their potential field of regard could extend to 360° for unusual circumstances. Because of the very wide field of regard required for operators in the tower, existing fields of view of widely available see-through HMDs, i.e. 20° to 40°, might be inadequate for the application.

2.5 Experimental tasks: Aircraft Detection and Landing Report task

The following experiments examine the effect of several FOV's on one aspect of local controllers' tasks, namely detection of landing aircraft, by subjects using an AR display in a simulated tower environment. The two experimental tasks designed for this study were intended to resemble some aspects of the actual tasks of tower controllers that might influence the design parameters of the applied HMDs. The chosen tasks include aircraft search, i.e. detection. A tower simulation displayed via a see-through head mounted display has been developed for use in this study that can allow users to view approaching aircraft as if they were actually located above the western control tower at Dallas Ft. Worth (DFW) airport (figure 6).

The air traffic controller is responsible for all landing aircraft. In this study two differing tasks approximating the actual activities involved with controlling landing aircraft are presented to subjects, For one task, called the Aircraft Detection task, the subject called out visual acquisition of a aircraft. For the other task, the Landing Report task, the subject called out visual confirmation of landing. Depending upon the nature and purpose of the task, different dependent variables (e.g. search time, reaction time, search rate, detection rate, fixation density) have been used to measure the observer's performance throughout different studies. However, all of these tasks have the properties of "spatial uncertainty reduction" and target certainty to a greater or lesser level (Monk, 1984). In this study detection time was used to measure observer's performance for the two experimental tasks.

In the Aircraft Detection task subjects are asked to identify new incoming aircraft that are appearing on the display at any given location and time. In the Landing Report task on the other hand, incoming aircraft that are already displayed need to

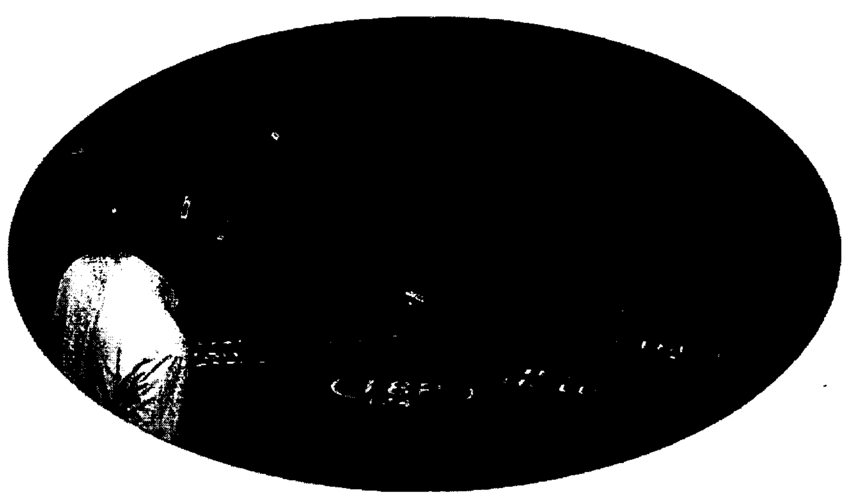

Figure 6. Graphic montage illustrating a subject watching approaching traffic from the DFW western ATC Tower.

be tracked until they land, which in this simulation means that they disappear from the display. Each landing occurs on one of four runways, also the aircraft are observed by subjects on their descending path. Therefore the location of the landing event is much less uncertain than in the Aircraft Detection task. The time of appearance in the Aircraft Detection task is entirely uncertain, whereas in the Landing Report task subjects have the possibility to make time estimates based on persistent speed and the distance to the runway locations where aircraft disappear. These runway locations were shown to subjects in the training and familiarization with the simulation (see chapter 3.5).

Cohn and Lasley (1986) made conclusions about uncertainty in visual search based on the theory of signal detectability (TSD) including the model of an ideal observer: The ideal observer must have exact knowledge of all signal parameters. Lacking this knowledge, the ideal observer must sample a larger than necessary set of channels to ensure the inclusion of the signal-bearing channels. Uncorrelated noise in the nonsignal-bearing channels leads to a number of predictions for the ideal observer. These predictions can then be compared to the performance of human observers. The optimal observer lacking knowledge of signal parameters is predicted to suffer a deficit in sensitivity. If the human observer behaves like the ideal photon detector of the TSD, uncertainty is predicted to have a significant influence on the observer's ability to detect the stimulus.

Cohn and Wardlaw (1985) investigated the effect of large spatial uncertainty on foveal luminance increment detectability in a detection experiment in which a target could be located at one of 140 equally likely, non-overlapping foveal spots. Their findings revealed decreased detection performance in conditions of spatial uncertainty. In accordance with the literature we could expect differences in aircraft detection performance for both experimental tasks, manifesting in increased detection times for the Aircraft Detection task in comparison to the Landing Report task due to more uncertainty of signal parameters, namely spatial location and time.

3. Experimental Methods

Figure 7 illustrates a schematic overview of the data flow for an augmented reality system in an ATC tower. In this figure the controller in the tower has a view of an

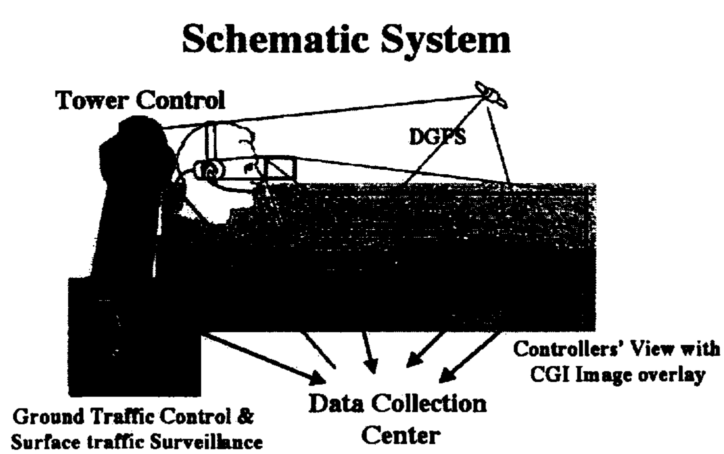

Figure 7. Proposed information flow for an augmented reality display in the airport control tower (after Krozel , Birtcil, Mueller, & Azuma, 1999).

airport through a semitransparent HMD. Differential GPS (DGPS) locates aircraft and ground vehicles, which a Data Collection Center (DAC) then monitors, providing and receiving information from traffic control and surveillance. The DAC is also preparing the computer generated imagery (CGI) used for the augmented reality display in the ATC tower.

The following study simulates the conditions of the airport tower associated with the use of the augmented reality display viewed in a laboratory. A binocular optical see-through display was used, but the aircraft and airport surface features were created by simulation.

3.1 Experimental Design and Identification of Variables

Participants in this study performed part of the task of local air traffic controllers: Their experimental task was to detect the appearance and disappearance of approaching and landing aircraft, presented in the HMD display. Since it was expected that restriction of the field of view would delay detection, the field of view was varied in an attempt to identify the value at which further decrease would no longer degrade performance.

In the first part of the present study the aircraft detection performance was expected to be related to the size of the subjects' FOV (experiment one). The aim was to determine for the specific task at the ATC tower, a FOV such that further increase would not improve performance. With different optical systems three binocular FOVs of 14°, 28° and 47° were produced and were tested in three independent groups of subjects of 9, 9 and 8 persons, respectively. The 14° and 28° conditions were presented to the subjects with 100% binocular overlap. With the available apparatus, however, the FOV of 47° became possible only by use of a divergent, partial overlap of 33%. Thus for the particular optics the overlap can be adjusted to obtain the largest possible FOV, without causing distortions in the periphery which would make the fusion of the two single-eyed views difficult. Divergent instead of convergent overlap was used because of technical limitations in the display.

Since divergent binocular overlap was needed to achieve the 47° condition, a subsidiary investigation comparing full and partial overlap displays was conducted to determine if this difference had an effect on performance for our particular experimental conditions (experiment two). Two additional experimental groups of 8 subjects each compared 14° and 28° binocular FOVs achieved either with divergent partial overlap of 46 %, or with 100% overlap.

The aircraft detection performance of the monocular view for 46% overlap was to be compared with detection performance in case of full binocular overlap. Thereby testing if luning caused difficulty for the ATC application using the specific hardware described in chapter 3.2.1.

Reaction times (RT) for appearances and landing of aircraft were measured separately. The two time values depend on the conditions for the FOV, however are looked at independently.

Monk (1984) describes a search trial as starting when the observer begins looking for a target and as ending when he indicates either that he has found it or that he is sure it does not appear in the display. In the following study detection time, in seconds, based on the appearance or disappearance of aircraft in the display was taken as the dependent measure for search performance. In this experiment the actual search trial started before the targets were displayed but only the reaction time after the actual appearance or disappearance of aircraft in the display was taken to account.

The full overlap conditions of experiment one were tested in a one-way analysis of variance. The partial overlap conditions of experiment two were evaluated in a separate two-way analysis of variance restricted to the 14° and 28° conditions and the partial and full overlap displays. Log transforms are used for statistical purposes to correct for skew in the RT data. In those cases in which the subjects failed to detect the aircraft targets, the frequencies of those failures were tabulated and analyzed in a Chi^2 contingency table.

3.2 Definition of Psychological and Statistical Hypotheses

3.2.1 Experiment One: Parameter Estimation

Restriction in the FOV is expected to delay aircraft detection for smaller FOVs.
Pair wise comparisons will be used to determine when the effect of field of view becomes asymptotic.

Experiment One:

14° FOV	28° FOV	47° FOV
Reaction time (μ1)	Reaction time (μ1)	Reaction time (μ1)

Null Hypothesis: Ho: $\mu1 = \mu2 = \mu3$

Experiment Two:

		Factor overlap	
		100% binocular overlap	46% binocular overlap
Factor	14° FOV	Reaction time (μ	Reaction time (μ2)
	28° FOV	Reaction time (μ	Reaction time (μ4)

Null Hypotheses: Factor overlap Ho: $\mu1 = \mu2,\ \mu3 = \mu4$

Factor FOV Ho: $\mu1 = \mu3,\ \mu2 = \mu4$

Factor interaction Ho: $\mu ij = \mu i + \mu j - \mu$

3.2.2 Experiment Two

Partial binocular overlap of 46% is expected to decrease detection performance in comparison to full binocular overlap in our simulated ATC application.

3.3 Participants in this study

42 subjects 18 to 59 participated in this study (18 female, 24 male). Participants were selected from laboratory personnel, college students and from the paid participant pool maintained by the Ames Contractor, Raytheon. Participants needed no prior experience in Air Traffic Control or simulated environments but they did need normal or corrected to normal vision. Subjects were blind to the specific experimental conditions. Several subjects were general aviation qualified pilots, who were distributed approximately evenly across the five separate groups. Subject gender was also balanced across groups. Neither classification is used for analysis. The data analysis for this experiment was conducted anonymously. The Simulation Sickness Questionnaire was edited so that the Social Security Number was not given to the monitors. Participants' names, if written on the SSQ by the subject were changed to Initial Codes for the analyses. Subjects signed a consent form informing them about the details of this voluntary study prior to starting the experiment.

3.4 Apparatus

3.4.1 Helmet mounted display

The see through HMD used in this study was custom made for specific research applications in the Advanced Displays and Spatial Perception Laboratory at NASA Ames Research Center.

All equipment was to prevent contact with dangerous voltages, sources of electromagnetic radiation or sharp objects in conformance with the Ames Human Subjects protocols. The equipment included in this study was mechanically adapted from commercially available head mounted displays; the Virtual Research V8, 50% see-through optics from Virtual Vision has a custom bright back-light allowing presentation of virtual objects with maximum luminance up to about 40 cd/m2. The luminescence of 1cd corresponds to the radiation of a black body at 1770° C with opening 1/60 cm2.

The HMD allowed adjustment of focus, interpupilary distance and binocular overlap ranging from 15% to 100%. The monocular fields of view were adjusted by replacing the combining optics with alternative elements of different focal length and field stops. Thereby, the binocular FOV could be changed keeping visual resolution close to 2.5'/pixel (1' corresponds to a Snellen visual acuity of 20/20). When placed on the users' head and attached to the cables, the system was balanced and weighted less than 1.3 kg. The weight varied somewhat depending upon the specific optics and cabling. The HMD construction was similar to that of a video camera monitor.

The FasTrak head position sensor was used with customary high performance driver software sampling head position at 120Hz using a predictive filter (Jung, Adelstein & Ellis, 2000). Using high frequency position sampling and predictive filtering, the effective system latency was reduced to less than about 15 ms. In contrast to most other HMD virtual environment implementations, the resulting imagery appeared essentially fixed in space during head movements, thereby removing one of the most common deficiencies in VE or AR implementations

3.4.2 Simulation environment

The virtual airport environment and other virtual objects were based on the view from the Dallas Ft. Worth (DFW) West

Tower and were created using World Tool Kit software on an SGI ONIX graphics computer with RE-2 graphics. Graphics complexity and system overhead requirements were managed so that the simulation could maintain a stable 60 Hz update rate.

The simulated aircraft activity was based on data collected from the Center TRACON Automation System (CTAS) Final Approach Spacing Tool (FAST), which represented a daily-use operational prototype air traffic control automation tool used at the Federal Aviation Administration (FAA) DFW Terminal Radar Approach Control (TRACON) facility.

The CTAS system uses software called the Communications Manager (CM) to handle most of the interprocess communication between the various CTAS programs. The CM can make connection to a daemon process, which serves data that is derived from an interface to the TRACON Automated Radar Tracking System (ARTS) computer system. This ARTS processes data from the Airport Surveillance Radar (ASR) for the TRACON controller operations. The CM can record all data, e.g., flight plans & radar tracks, from the ARTS into an ASCII history file. For this experiment the CTAS was connected to the described live Dallas Ft. Worth data source, recording data during heavy traffic load on March 16th, 2000.

The Tower Simulation Software (TSS) running the virtual augmentation display was designed to use a CM history file as input. The TSS typically read ARTS and, or ASR track data, which was updated every 4.8 seconds, and interpolated 'in-between' positions so that the virtual 3-D aircraft could be animated with 'real-time' frame rates, i.e., more than 30 frames per second. The air traffic control tower (ATCT) software also performed several other filtering and smoothing operations to compensate for radar processing artifacts.

The TSS used pre-recorded 'live' CM data in this experiment. The virtue of using pre-recorded 'live' data was the repeatable preservation of actual flight patterns and behavior for every participating subject, and the representative presentation of controller tasks and workload training.

The file of aircraft trajectories was edited to produce separate training and experimental files, which displayed comparable amounts of aircraft. Runs based on both files preserved the general directions and locations of aircraft using different aircraft identifications and sequences to minimize the effect of learning of specific aircraft maneuvering.

To take into consideration that the participating subjects were not professional controllers only two landing aircraft were required to be monitored at any time in addition to their concurrent task of detecting up to 4 appearing aircraft.

The experiment was conducted within a cleared laboratory room so that the walls in the directions that the subjects needed to view were mainly blank. The virtual imagery made them seem somewhat transparent as the subjects " looked through" them to see the virtual aircraft and runway layout, which was presented so as to appear approximately at their correct distance, i.e. several miles away. The resolution of the display system precluded a precise stereo calibration of the visual imagery for the distances viewed on the display but this fact was not an issue because of the relatively long distances to the aircraft (>1 km).

3.5 Experimental Procedure

The experimental task was designed to represent a part of the job of Air Traffic Controller's work. Subjects performed the task in a 25 min training-run followed by a 25 min experimental-run. The 25 minutes training was sufficient to stabilize response timing as verified below. This fact can be demonstrated by the data plots of performance stored event-wise as a function of time in the experimental file: No change in performance over time were reported during the experimental run. Therefore, subjects seemed to be able to maintain a certain level of performance over the 25 minutes experimental trial. These facts suggest that no training or fatigue effects impacted the measured data.

To aid the subjects in orientation a texture map of the runways taken from an FAA airport map diagram was displayed (Fig 5, Appendix B). Also, subjects that from their viewing position all traffic that they need to monitor appeared within an approximately 200° horizontal field of regard. Participants were instructed to identify two events by button presses: 1) the appearance of designated aircraft within their field of regard (Aircraft Detection Task) and 2) the landing of a specific approaching aircraft (Landing Report Task) (see Appendix A: Instructions). The display presented 16 different aircraft targets whose appearance had to be detected by the subject. Subjects were requested to identify the landing of 32 different aircraft, 29 of these were used for statistical analysis. Both sets of aircraft were imbedded in evolving traffic patterns containing from 12 to 25 aircraft at any given time. Displays used for search tasks can vary in complexity from a blank screen containing a small patch of light to highly sophisticated displays. Displays for which the target is the only item present are known as impoverished. Cluttered displays are characterized by the presence of confusing non-targets in the display leading to competition search. The latter was the case in this study. A system of paper-flight strips similar to those used in a tower was used to identify the aircraft that subjects needed to monitor. Reaction times between the occurrence of the targeted events, i.e. the appearance of or landing of a designated aircraft, and the subjects' responses identifying the events were measured.

The use of head mounted displays for visual display of experimental tasks may cause discomfort after approximately 25 min of continuous use because of helmet weight. However, a break between the test-run and the experiment-run was given and every effort made to ensure the subjects comfort throughout the experiment. Pre- and post-experiment Simulation Sickness Questionnaires (Kennedy, Lane, Berbaum & Lilienthal, 1993) were given to all subjects.

4. Results

Table 1 presents the means and standard deviations (SD) for the 14°, 28° and 47° conditions tested in the first part of this experiment. Both parameters are calculated separately for aircraft detection and landing report tasks in every group investigated, and before and after log transformation. The distribution of search times produced in this study by measuring reaction times from the moment of appearance/disappearance of an aircraft on the display until the detection of the same, is reported to be usually highly skewed, approximating a negative exponential distribution. Because of the large amount of skew present in search-time distributions, Monk (1984) suggests to either use non-parametric statistics, or the median as the reported measure, or to transform the data logarithmically prior to analysis of variance. The latter option was chosen in this study.

Table 1. Aircraft Detection and Landing Report results for Experiment 1.

Aircraft Detection:

	FOV conditions		
	14° FOV	28° FOV	47° FOV
Means in seconds (SD)	49.18 (22.68)	32.09 (12.47)	29.08 (9.88)
Log transformation: Means in seconds (SD)	3.81 (0.44)	3.40 (0.39)	3.32 (0.35)

Landing Report:

	FOV conditions		
	14° FOV	28° FOV	47° FOV
Means in seconds (SD)	9.93 (5.34)	2.84 (0.79)	1.89 (0.62)
Log transformation: Means in seconds (SD)	2.18 (0.52)	1.00 (0.32)	0.59 (0.31)

Table 2. Aircraft Detection and Lading Report results for Experiment 2.

Aircraft Detection:

	FOV conditions			
	Full binocular overlap		Partial (46%) binocular overlap	
	14° FOV	28° FOV	14° FOV	28° FOV
Means in seconds (SD)	49.18 (22.68)	32.09 (12.47)	57.25 (27.05)	40.31 (19.08)
Log transformation: Means in seconds (SD)	3.81 (0.44)	3.40 (0.39)	3.94 (0.50)	3.61 (0.45)

Landing Report:

	FOV conditions			
	Full binocular overlap		Partial (46%) binocular overlap	
	14° FOV	28° FOV	14° FOV	28° FOV
Means in seconds (SD)	9.93 (5.34)	2.84 (0.79)	6.79 (3.13)	4.54 (3.02)
Log transformation: Means in seconds (SD)	2.18 (0.52)	1.00 (0.32)	1.79 (0.58)	1.37 (0.52)

Table 2 shows the means and standard deviations (SD) for the full and partial FOV conditions tested in the second part of this investigation. Parameters are being calculated before and after log transformation and separately for aircraft detection and landing report tasks.

Figure 8 (left) plots a significant FOV effect for aircraft detection calculated in a one-way ANOVA, ($F(2,23) = 3.908$, $p < .035$; log transformation: $F(2,23) = 3.835$, $p < .037$). Figure 8 (right) shows a similar significant effect of the FOV conditions on the Landing Time Report calculated with a one-way ANOVA for the FOV ($F(2,23) = 16.511$, $p < .001$; log transformation: $F(2,23) = 37.04$, $p < 0.001$) (Appendix C).

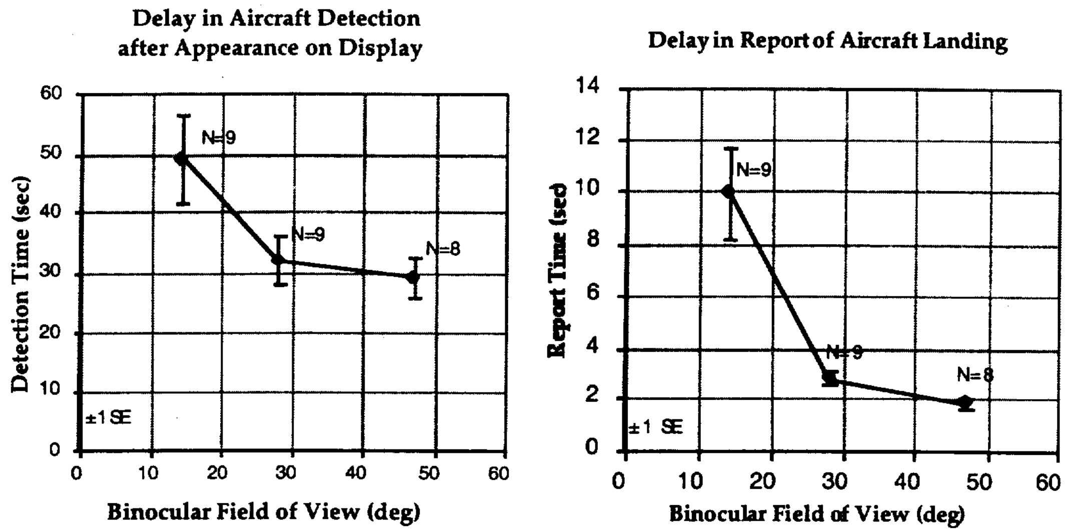

Figure 8. The two tasks tested in this study resulted in significant FOV effects on measured performance by reaction times.

Table 3. Scheffé test results.

Aircraft Detection:

	Mean Difference	Critical Difference	P-Value P<.1*, P<.05**, P<.01***
14° FOV, 28° FOV	-.178	.211	.1109
28° FOV, 47° FOV	.035	.218	.9138
14° FOV, 47° FOV	.213	.218	.0558*

Landing Report:

	Mean Difference	Critical Difference	P-Value P<.1*, P<.05**, P<.01***
14° FOV, 28° FOV	-.510	.213	< .0001***
28° FOV, 47° FOV	.177	.220	.1320
14° FOV, 47° FOV	.687	.220	< .0001***

A Scheffé test was calculated for pair wise comparisons between the 14°, 28° and 47° conditions on log transformed data. Table 3 shows the results for the Aircraft Detection and the Landing Report tasks (Appendix F).

A 2-way ANOVA was calculated for Aircraft Detection with 14° and 28° FOV using either full or partial overlap (Table 4). The FOV effect remained significant ($F(1,30) = 5.667$, $p < .024$; log transformation: $F(1,30) = 6.047$, $p < .020$). Aircraft Detection data for full vs. partial binocular overlap conditions did not differ significantly ($F(1,30) = 1.294$, $p < .264$; log transformation: $F(1,30) = 1.231$, $p < .276$). No significant results were found for the interactions FOV and binocular overlap in this task (F (1,30) = 0.00, p < .991; log transformation: F (1,30) = 0.05, p < .824) (Appendix D).

A 2-way ANOVA was calculated for Landing Time Reports for 14° and 28° FOV with full and partial overlap (Table 4). The results for the FOV effect were significant (F (1,30) = 16.142, p < .001; log transformation: F (1,30) = 23.579, p < .001). Data for full vs. partial binocular overlap did not differ significantly (F (1,30) = 0.367, p < .549; log transformation: F (1,30) = 0.004, p < .95). Before the log transformation no significant interactions were detected. However, after the log transformation a significant interaction was found (F (1,30) = 4.0, p < .052; log transformation: F (1,30) = 5.065, p < .032). This interaction suggested a benefit to partial overlap and is not consistent with the Aircraft Detection results.

Table 4. Results for 2-way Anova.

Aircraft Detection:

Conditions					log transform.	
			F	p<	F	p<
FOV (means in seconds)	14° FOV	28°FOV	5.667	0.024	6.047	0.020
	52.98	35.96				
Overlap (means in seconds)	Full Overlap	Partial Overlap	1.294 (NS)	0.264	1.231 (NS)	0.276
	40.63	48.78				
FOV x Overlap (means in seconds)	Full Overlap	Partial Overlap	0.0 (NS)	0.991	0.05 (NS)	0.824
14°	49.18	57.25				
28°	32.09	40.31				

Landing Report:

Conditions					log transform.	
			F	p<	F	p<
FOV (means in seconds)	14° FOV	28°FOV	16.142	0.001	23.579	0.001
	8.45	3.64				
Overlap (means in seconds)	Full Overlap	Partial Overlap	0.367 (NS)	0.549	0.004 (NS)	0.950
	6.39	5.66				
FOV x Overlap (means in seconds)	Full Overlap	Partial Overlap	4.078 (NS)	0.052	5.065	0.032
14°	9.93	6.79				
28°	2.84	4.54				

For cases in which the subjects failed to detect the aircraft targets, the frequencies of the detection failures were tabulated and analyzed in a Chi^2 contingency table for the conditions of the first as well as of the second experimental investigation. Contingencies for Aircraft Detection and Landing Report tasks were calculated separately and corrections were used if the expected frequency was lower than 5. The first experiment showed a significance for the Aircraft Detection task ($Chi_{(2)}{}^2 = 6.38$) but no significance in the Landing Report task ($Chi_{(2)}{}^2 = 0.7$), the critical $Chi_{(2)}{}^2$ value was 5.99.

In the second experiment neither contingencies in Aircraft Detection task ($Chi_{(1)}{}^2 = 0.32$) nor in the Landing Report task ($Chi_{(1)}{}^2 = 0.14$) reached significance ($Chi_{(1)}{}^2$ crit. = 3.84) (Appendix H).

Reaction times (RTs) for the Landing Report and Aircraft Detection task correlated significantly positive across subjects (Figure 9) (R = 0.61, p<.001, df= 39).

Simulator induced side effects were evaluated by the Simulation Sickness Questionnaire (SSQ). The SSQ results appeared to be idiosyncratic showing some base-line effects but no effects of experimental variable. Furthermore, the researcher administering the questionnaire noted that subjects appeared inconsistent in their responses. I.e., subjects who actually appeared to be suffering simulation sickness symptoms choose low scores while other subjects who did not appear to have such symptoms choose high scores. Accordingly, we have decided to defer further analysis or use of the questionnaire until we can improve its administration to obtain results with better face validity.

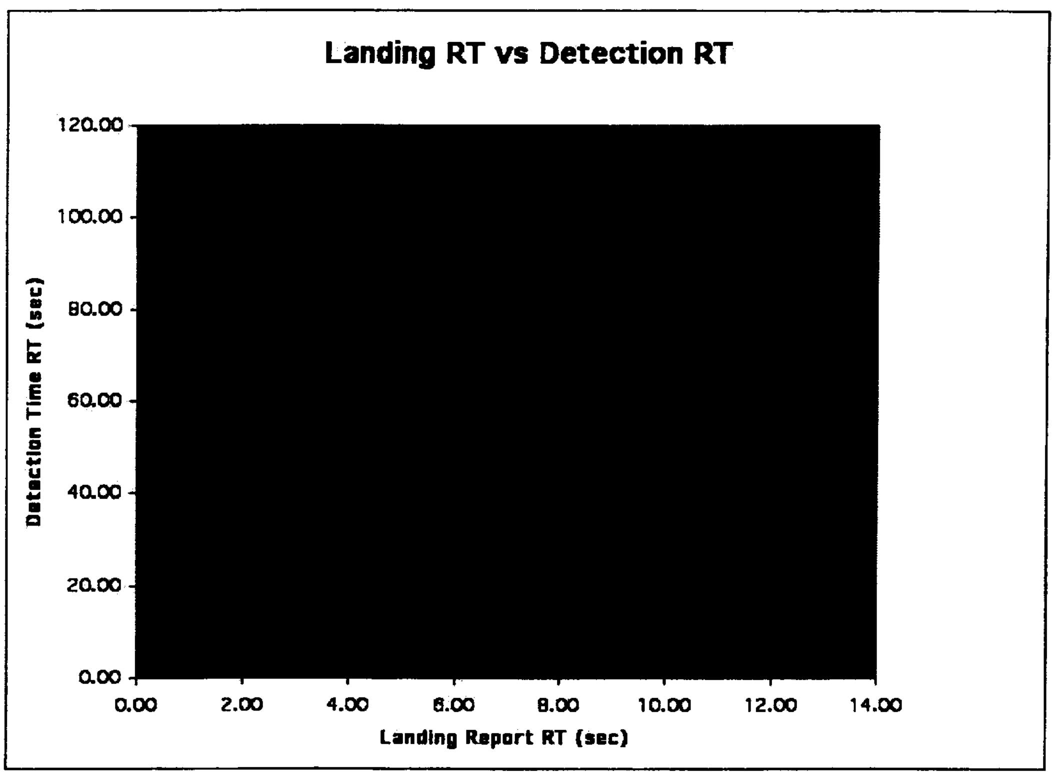

Figure 9. Correlation between Landing Report RT and Aircraft Detection RT above subjects (before log transformation). R= 0.61, p<.001, df= 39.

5. Discussion

The results of this study support design recommendations for the required FOV of a HMD for use in an ATC tower. The FOV effects measured for both tasks, resembling parts of the activities of air traffic controllers, suggest that aircraft detection performance will change very little for fields of view greater than 47°. Such a field has been easily achievable with existing head-mounted see-through displays, e.g. the V8 or Virtual Research or the Kaiser Proview X, particularly if a partial overlap system is used. Production trends, however, indicate that mainly smaller FOVs in LCD optics for HMDs will be produced in the future (B. Bassett, personal communication, Spring 2001). With this knowledge of decreasing availability of wide FOV displays, it becomes even more important to investigate this possibility to increase the total FOV of the smaller optics through the use of partial overlap systems. The second experiment suggests that divergent partial overlap of 46% may be an acceptable option to use in this particular task environment and can therefore be recommended to HMD designers.

5.1 Experiment One

5.1.1 FOV effects

The significant FOV results for the first experiment were analyzed in more detail with Scheffé tests, revealing significant differences in the Landing Report data ($p<.01$) between the 14° and 28° as well as the 14° and 47°conditions. The comparisons between the FOV conditions for the Aircraft Detection task showed significant differences ($p<.10$) only between 14° and 47° conditions. There was no statistically significant difference between 28° and 47° in both tasks. In light of the small standard errors, which constrain extrapolation from these measurements, these results suggest further increases in total FOV will not produce major performance benefits.

A point of critique for the experimental design and the reported results is that full overlap conditions of 14° and 28° were compared to the 47° condition achieved by only a 33% binocular overlap. This design was chosen due to restrictions of the given equipment. Unfortunately we do not know if the performance would have been better with a 100% overlap in the 47° condition. Nevertheless, no consistent performance differences between the 100% and partial overlap conditions were found in experiment two. This suggests that a comparison of aircraft detection performance in the three conditions of experiment one is a suitable approach, given the technical limitations. Still, it would be an instructive to test the 47° condition achieved by full binocular overlap.

If a significant difference between the 28° and 47° conditions were found in this study, at least one other, wider FOV condition would have been attempted to test in order to detect the FOV value at which no further significant decrease in performance would occur. Such a field of view, however, would have been compromised by significant optical distortion because of the need to bring the distorted peripheral image into the central vision of the user. In any case, to fully verify the suggestion of an asymptotic course of aircraft detection performance after 47°, another wider FOV would have been a meaningful addition to the experimental design. Unfortunately such a condition was not achievable without distortion and could be suggested for subsequent research.

5.1.2 Undetected aircraft and number of detectable events

Comparisons between the 28° and 14° conditions might have been differentially effected by the numbers of undetected aircraft. This possibility was investigated by a Chi^2 test that shows a significant increase in the number of undetected aircraft for the narrower FOV conditions for the Aircraft Detection task, but no significance for the Landing Report task. Undetected aircraft represent valuable information for the estimation of performance in our ATC application. In fact they can be interpreted as a significant failure instead of just a decrease in aircraft detection performance! Therefore, these results could be interpreted as an indicator that there could be a difference in the performance between the 14° and 28° conditions in the Aircraft Detection task that did not show up in the Scheffé tests due to a loss of data that would have increased the average detection times. Also, there was a lower number of possible events in the Aircraft Detection task (16 events) as compared to the Landing Report task (28 events) but the numbers of undetected events was similar or even higher in the Aircraft Detection task for almost all conditions. Differing numbers of undetected aircraft events might be caused by a differing task difficulty in both tasks.

5.1.3 Differences in task difficulty and possibility for performance trade-off between tasks

Differences in the two tasks are apparent in the measured reaction times. The instructions suggested that subjects always needed to closely track aircraft in the Landing Report task. Because aircraft would always disappear close to one of the four runways, subjects' knew where an event could take place but not when. In the Aircraft Detection task, on the other hand subjects knew neither where nor when an aircraft would appear. Therefore, this search task could be considered more difficult due to spatial and temporal uncertainty (Cohn & Wardlaw, 1985). The experimenter conducting the experiments observed that most subjects tended to focus first on the Landing Report task and only when subjects had detected the landing aircraft and knew where they were located would they then begin the search needed for the Aircraft Detection task. This observation led to the question of a possible performance trade-off between the measures for both tasks because subjects' focusing on one task could lead to poorer performance on the other task. This effect would manifest itself in a negative correlation between reaction times for both tasks. However, a statistically significant positive correlation between the Aircraft Detection task and Landing Report task shows that subjects achieved either high or low performance (RTs) in both tasks (Figure 9). This result withstands log transforms calculated to balance variances (Appendix G). These results suggest that individual subjects did not trade off performance on the two tasks, i. e. adequate resources for both tasks existed, a situation similar to trained controllers. The lack of evidence of a trade off could mean that neither task was sufficiently difficult to use up a large fraction of the subjects processing resources.

In the Aircraft Detection task, RTs (see above) and variances are higher than in the Landing Report task. Besides the discussed differences in task difficulty that could have influenced these results, the experiment monitor observed subjects pressing the mouse button indicating the detection of an aircraft, even though they had not seen the aircraft but still put the card aside after several minutes. This behavior would lead to a measure of a very high RT for an event that was actually undetected and would explain the few very high numbers in reaction times in this data. Nevertheless, the log transformation corrected for the positive skew in our reaction time distribution.

The two tasks were initiated asynchronously but because of their temporal extent substantially overlapped. In fact, this pattern simulates tasks actually experienced within the airport tower environment.

5.2 Experiment Two

The subsidiary experiment, comparing full with partial overlap systems did not find any consistent performance difference between the 100% and partial overlap conditions. The FOV effects on the other hand remained. Only the log transformed interaction in the Landing Report task achieved significance. In fact, the observed interaction suggested a slight benefit to partial overlap. A result that was completely unexpected for the experimenters and no explanation can be found at this point, especially because the effect occurred only in the Landing Report task and only in the 14° condition. Further investigations would be needed to prove that this effect is either spurious or due to variables that haven't been controlled in this study.

The failure to discriminate the two conditions could mean that the binocular rivalry sometimes called luning (Velger, 1998, p.56-58) associated with the partial overlap conditions did not materially effect performance for the overlap that was used in our application. One reason the luning might not have had a performance impact is that in the see-through conditions used, the partially overlapping fields were not completely filled with graphic objects, especially in the view above the airport where only small bright, moving aircraft and data tags were displayed. Thus, the margins of the overlapping fields were not always visible.

Some lunning was subjectively visible to the subjects in the partial overlap conditions, but we find no evidence that it introduced major visibility problems for the application we examined. Consequently, we suggest designers consider partial overlap systems to achieve the approximately 50° binocular FOV needed for the present application.

5.3 Future Outlook

The next step in the development of a head-mounted augmented reality display for the ATC tower would be the integration of a display system like that used for the present experiments into a system using a real-time position data source from moving vehicles, aircraft or even ground vehicles, visible from a real tower. Such a system would allow examination of the integration issues that were finessed in the present study and allow evaluation of the ultimate utility of this concept introduced by Llyod Hitchcock some 20 years ago, but which has only become technically feasible in the past few years.

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7. Appendix

Appendix A: Instructions

Thank you for participating in our experiment.

We would like you to start with filling out a questionnaire about how you feel right now. Once you are done with that we will explain the experimental task to you.

Before we start with the actual experiment, which will take approximately 25 min, we are going to explain the task, and you will have the chance to practice in the simulator and ask questions. If needed, we will repeat the training in the simulator to make sure you know exactly what to do in the experiment. Once you understand the task we would like you to keep performing it in the same way throughout the entire experiment.

We will help you put on a head-mounted display (HMD) and adjust it to fit your head. Please make sure it is comfortable to wear for the next 30 min. You will be able to take a break after the training-phase is completed.

The HMD is a see-through display, which means that you can see your actual environment (in this case the laboratory) as well as the displayed environment. The display will show the Dallas Ft. Worth (DFW) airport from the perspective of the control tower.

You will pretend to be an air-traffic-controller who is in charge of the specific task of detecting approaching aircraft, knowing where they are, and communicating their landing. You will be shown a map of the airport DFW and the runways where approaching aircraft are to be expected will be pointed out to you before you start practicing the task.

You will see a number of aircraft, with data tags that inform you about their aircraft identification (e. g., AAL17). On the desk in front of you, you will find cards with such aircraft identifications. There are cards with aircraft ID's written in black and in red colors. The colors indicate different tasks:

You start with the first two cards written in black (A and B), as soon as A has landed you will pick up the next card and find aircraft C. Once one of the two aircraft (B or C) has landed you will pick up the next card written in black for aircraft D and continue until you have used all cards. You need to constantly move your focus from one aircraft to the other. Do not keep your eyes on one airplane.

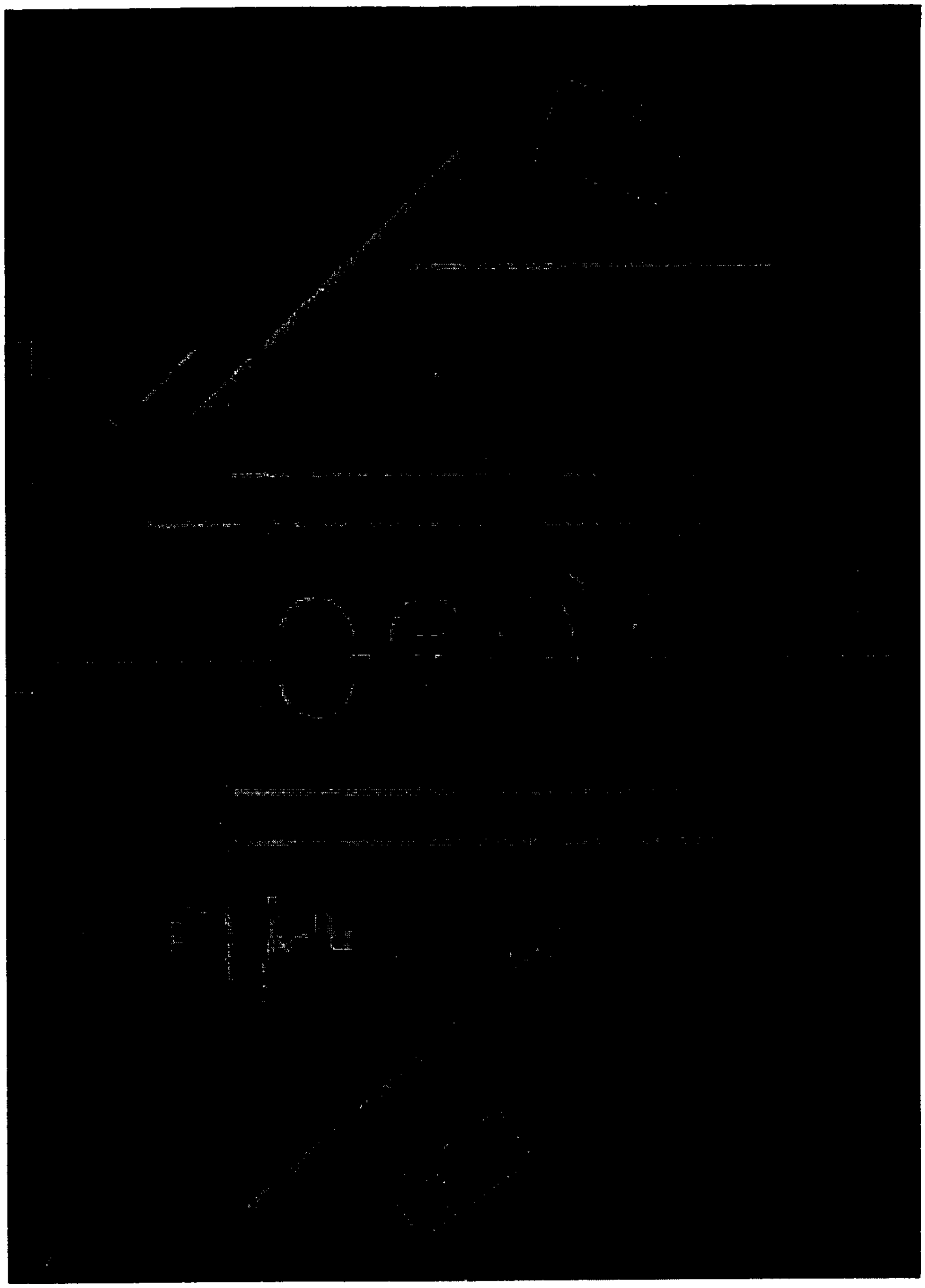
The aircraft will disappear from the display right before they approach the runway. Press the left mouse-button as soon as you notice the disappearing and tell us which airplane disappeared: "AAL 17 landed". Then put the card "AAL 17" aside and you pick up the next card and proceed in the same manner until all cards have been used.

In addition to the cards written in black, you will find cards written in red color in the same pile. These cards imply that there is a new aircraft appearing soon (e.g., EGF 61) and you need to detect it as fast as possible. As soon as you see the aircraft, press the right mouse-button and say: "EGF 61 detected" and put the card "EGF 61" aside.

Even though we want you to detect new airplanes as fast as possible it is essential for you to always track the two landing airplanes (with the cards written in black) and to communicate their landing with a left mouse-click as well as verbally. It is important that you pick up the next black written card as soon as one aircraft disappeared, so you are always looking at two landing aircraft at the same time.

In addition to the verbal response for landed "black" and appeared "red" aircraft we would like you to tell the monitor also about every new aircraft that the "black" cards imply to look for as soon as you can see it in the sky, e. g., "I see AAL17" so that the monitor knows exactly which aircraft you are observing. After the experiment we would like you to fill out the second part of the questionnaire. Thank you!

Appendix B: Map of Dallas Ft. Worth airport (DFW)



Appendix C: Anova for Experiment One

```
awk '$3 ~ /f/{print $1,$2,$5}' < all* | anova subj view
appearRT
SOURCE: grand mean

SmFOV -14deg
MFOV - 28
WFOV - 47

view        N      MEAN         SD         SE
           26    37.0796    17.9959     3.5293

SOURCE: view
view        N      MEAN         SD         SE
mFOV        9    32.0889    12.4743     4.1581
smFOV       9    49.1789    22.6811     7.5604
wFOV        8    29.0825     9.8752     3.4914

FACTOR  :      subj      view     landRT
LEVELS  :        26         3         26
TYPE    :    RANDOM   BETWEEN       DATA

SOURCE                 SS      df          MS          F
p
================================================================
==
mean          35747.3453       1   35747.3453   136.057
0.000  ***
s/v            6042.9862      23     262.7385

view           2053.3288       2    1026.6644     3.908
0.035  *
s/v            6042.9862      23     262.7385
```

```
awk '$3 ~ /f/{print $1,$2,log($5)}' < all* | anova subj view
appearRT

SOURCE: grand mean
view        N       MEAN        SD         SE
           26     3.5168    0.4373     0.0858

SOURCE: view
view        N       MEAN        SD         SE
mFOV        9     3.4019    0.3888     0.1296
smFOV       9     3.8079    0.4368     0.1456
wFOV        8     3.3185    0.3484     0.1232

FACTOR    :        subj        view       landRT
LEVELS    :         26           3          26
TYPE      :      RANDOM     BETWEEN       DATA

SOURCE                   SS       df            MS          F
p
=================================================================
==
mean               321.5637        1      321.5637   2062.651
0.000  ***
s/v                  3.5857       23        0.1559

view                 1.1958        2        0.5979      3.835
0.037  *
s/v                  3.5857       23        0.1559
```

```
awk '$3 ~ /f/{print $1,$2,$4}' < all* | anova subj view
landRT

SOURCE: grand mean
view        N       MEAN        SD         SE
           26      5.0046      4.7919     0.9398

SOURCE: view
view        N       MEAN        SD         SE
mFOV        9      2.8433      0.7944     0.2648
smFOV       9      9.9344      5.3375     1.7792
wFOV        8      1.8900      0.6238     0.2206

FACTOR   :        subj        view    appearRT
LEVELS   :          26           3          26
TYPE     :      RANDOM     BETWEEN        DATA

SOURCE                    SS      df            MS          F
p
================================================================
==
mean               651.2006        1      651.2006     63.550
0.000  ***
s/v                235.6806       23       10.2470

view               338.3758        2      169.1879     16.511
0.000  ***
s/v                235.6806       23       10.2470
```

```
awk '$3 ~ /f/{print $1,$2,log($4)}' < all* | anova subj view
landRT

SOURCE:  grand  mean
view         N        MEAN          SD          SE
            26      1.2841      0.7853      0.1540

SOURCE:  view
view         N        MEAN          SD          SE
mFOV         9      1.0032      0.3222      0.1074
smFOV        9      2.1800      0.5170      0.1723
wFOV         8      0.5922      0.3126      0.1105

FACTOR    :       subj        view     appearRT
LEVELS    :         26           3           26
TYPE      :     RANDOM     BETWEEN         DATA

SOURCE                   SS       df            MS          F
p
==============================================================
==
mean                42.8717        1       42.8717    269.975
0.000  ***
s/v                  3.6524       23        0.1588

view                11.7642        2        5.8821     37.041
0.000  ***
s/v                  3.6524       23        0.1588
```

Appendix D: 2way Anova for Experiment Two

```
awk '$2 ~ /[smpP]/ {print $1,$2,$3,log($5)}' < all* | anova
subj view overlap appearRT

SOURCE: grand mean
view     overlap     N       MEAN        SD        SE
                     34      3.6844      0.4714    0.0809

SOURCE: view
view     overlap     N       MEAN        SD        SE
mFOV                 17      3.4975      0.4190    0.1016
smFOV                17      3.8713      0.4567    0.1108

SOURCE: overlap
view     overlap     N       MEAN        SD        SE
          f          18      3.6049      0.4523    0.1066
          p          16      3.7738      0.4909    0.1227

SOURCE: view overlap
view     overlap     N       MEAN        SD        SE
mFOV     f            9      3.4019      0.3888    0.1296
mFOV     p            8      3.6050      0.4512    0.1595
smFOV    f            9      3.8079      0.4368    0.1456
smFOV    p            8      3.9427      0.4976    0.1759

FACTOR   :        subj        view     overlap    appearRT
LEVELS   :          34           2           2          34
TYPE     :      RANDOM     BETWEEN     BETWEEN        DATA

SOURCE                  SS       df              MS           F
p
==============================================================
==
mean              461.5454        1        461.5454    2349.074
0.000  ***
s/vo                5.8944       30          0.1965

view                1.1882        1          1.1882       6.047
0.020  *
s/vo                5.8944       30          0.1965

overlap             0.2418        1          0.2418       1.231
0.276
s/vo                5.8944       30          0.1965

vo                  0.0098        1          0.0098       0.050
0.824
```

s/vo	5.8944	30	0.1965

```
awk '$2 ~ /[smpP]/ {print $1,$2,$3,$5}' < all* | anova subj
view overlap appearRT

SOURCE: grand mean
view     overlap     N        MEAN          SD          SE
                     34     44.4671      22.0561      3.7826

SOURCE: view
view     overlap     N        MEAN          SD          SE
mFOV                 17     35.9588      15.9697      3.8732
smFOV                17     52.9753      24.3821      5.9135

SOURCE: overlap
view     overlap     N        MEAN          SD          SE
         f           18     40.6339      19.8148      4.6704
         p           16     48.7794      24.2444      6.0611

SOURCE: view overlap
view     overlap     N        MEAN          SD          SE
mFOV     f            9     32.0889      12.4743      4.1581
mFOV     p            8     40.3125      19.0832      6.7469
smFOV    f            9     49.1789      22.6811      7.5604
smFOV    p            8     57.2462      27.0467      9.5624

FACTOR   :        subj        view     overlap    appearRT
LEVELS   :          34           2           2          34
TYPE     :      RANDOM     BETWEEN     BETWEEN        DATA

SOURCE                  SS        df              MS           F
p
=================================================================
==
mean            67228.8578         1      67228.8578     154.784
0.000  ***
s/vo            13030.1902        30        434.3397

view             2461.2623         1       2461.2623       5.667
0.024  *
s/vo            13030.1902        30        434.3397

overlap           562.0146         1        562.0146       1.294
0.264
s/vo            13030.1902        30        434.3397

vo                  0.0517         1          0.0517       0.000
0.991
s/vo            13030.1902        30        434.3397


awk '$2 ~ /[smpP]/ {print $1,$2,$3,$4}' < all* | anova subj
view overlap landRT
SOURCE: grand mean
view     overlap     N        MEAN          SD          SE
                     34      6.0468       4.3226      0.7413

SOURCE: view
view     overlap     N        MEAN          SD          SE
mFOV                 17      3.6412       2.2531      0.5465
smFOV                17      8.4524       4.6004      1.1158
```

SOURCE: overlap

view	overlap	N	MEAN	SD	SE
	f	18	6.3889	5.1975	1.2251
	p	16	5.6619	3.1926	0.7981

SOURCE: view overlap

view	overlap	N	MEAN	SD	SE
mFOV	f	9	2.8433	0.7944	0.2648
mFOV	p	8	4.5388	3.0237	1.0691
smFOV	f	9	9.9344	5.3375	1.7792
smFOV	p	8	6.7850	3.1329	1.1076

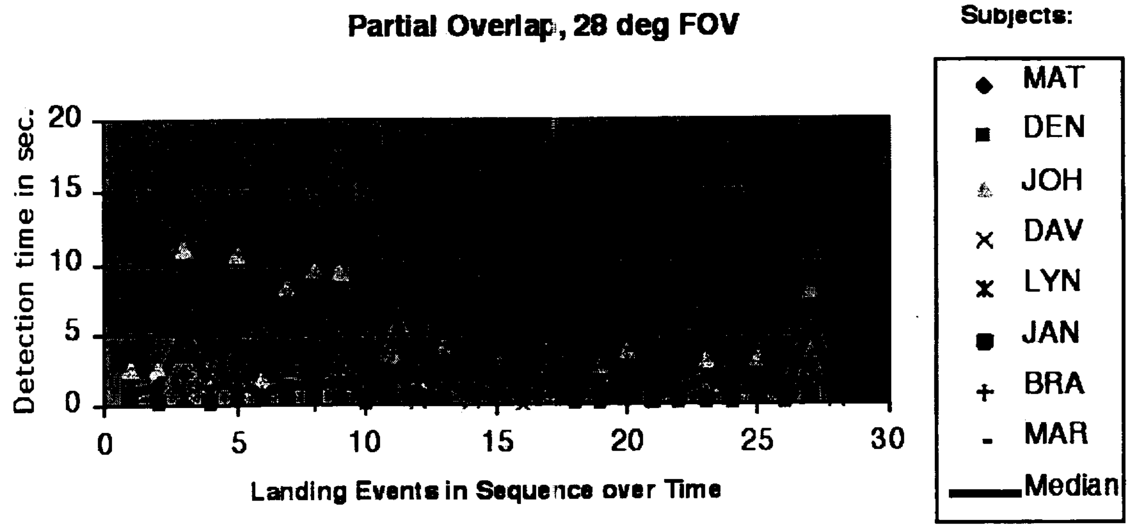
FACTOR :	subj	view	overlap	landRT
LEVELS :	34	2	2	34
TYPE :	RANDOM	BETWEEN	BETWEEN	DATA

SOURCE	SS	df	MS	F	p
mean	1243.1544	1	1243.1544	101.992	0.000 ***
s/vo	365.6633	30	12.1888		
view	196.7531	1	196.7531	16.142	0.000 ***
s/vo	365.6633	30	12.1888		
overlap	4.4771	1	4.4771	0.367	0.549
s/vo	365.6633	30	12.1888		
vo	49.7069	1	49.7069	4.078	0.052
s/vo	365.6633	30	12.1888		

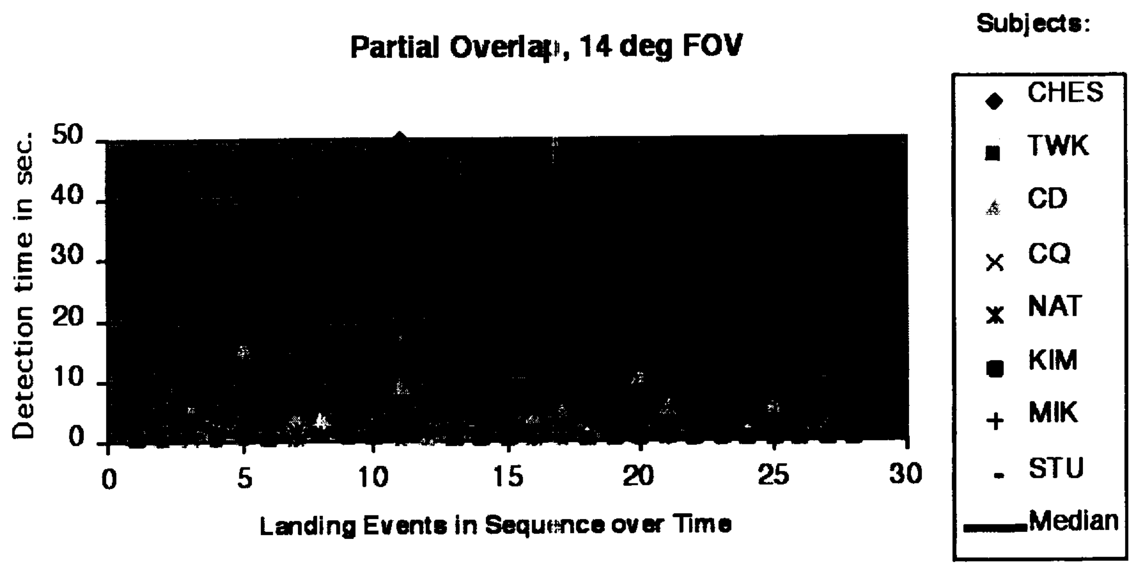
```
awk '$2 ~ /[smpP]/ {print $1,$2,$3,log($4)}' < all* | anova
subj view overlap landRT
SOURCE: grand mean
view     overlap      N        MEAN         SD          SE
                      34      1.5866      0.6555      0.1124

SOURCE: view
view     overlap      N        MEAN         SD          SE
mFOV                  17      1.1771      0.4563      0.1107
smFOV                 17      1.9960      0.5673      0.1376

SOURCE: overlap
view     overlap      N        MEAN         SD          SE
         f            18      1.5916      0.7357      0.1734
         p            16      1.5809      0.5761      0.1440

SOURCE: view overlap
view     overlap      N        MEAN         SD          SE
mFOV     f             9      1.0032      0.3222      0.1074
mFOV     p             8      1.3727      0.5241      0.1853
smFOV    f             9      2.1800      0.5170      0.1723
smFOV    p             8      1.7891      0.5810      0.2054

FACTOR   :         subj         view      overlap      landRT
LEVELS   :           34            2            2          34
TYPE     :       RANDOM      BETWEEN      BETWEEN        DATA

SOURCE                    SS       df              MS          F
p
=============================================================
==
mean                 85.5829        1         85.5829    353.947
0.000  ***
s/vo                  7.2539       30          0.2418

view                  5.7012        1          5.7012     23.579
0.000  ***
s/vo                  7.2539       30          0.2418

overlap               0.0010        1          0.0010      0.004
0.950
s/vo                  7.2539       30          0.2418

vo                    1.2246        1          1.2246      5.065
0.032  *
s/vo                  7.2539       30          0.2418
```

Appendix E: Data Plots, Medians (Detection time in seconds) over subjects for sequence of events over time

Median (Detection time in seconds) over Subjects for Landing Events in Sequence over Time



Median (Detection time in seconds) over Subjects for Appearance Events in Sequence over Time



Appendix F: Scheffé Tests

Scheffe for appear RT
Effect: FOV
Significance Level: 5 %

	Mean Diff.	Crit. Diff	P-Value	
mFOV, smFOV	-.178	.211	.1109	
mFOV, wFOV	.035	.218	.9138	
smFOV, wFOV	.213	.218	.0558	

Scheffe for land RT
Effect: FOV
Significance Level: 5 %

	Mean Diff.	Crit. Diff	P-Value	
mFOV, smFOV	-.510	.213	<.0001	S
mFOV, wFOV	.177	.220	.1320	
smFOV, wFOV	.687	.220	<.0001	S

Appendix G: Correlation between RT means of Aircraft Detection and Landing Report tasks across Subjects

Reaction time means across Subjects:

Subjects	land_RT in seconds	appear_RT in seconds	Log transformed Landing report RT	Log transformed Aircraft Detection RT
ARJ	2.77	16.72	0.44	1.22
BEN	1.48	39.08	0.17	1.59
CHE	3.79	40.06	0.58	1.60
JAR	2.88	27.50	0.46	1.44
KEI	2.69	22.81	0.43	1.36
KIM	1.77	56.59	0.25	1.75
LAR	3.25	29.49	0.51	1.47
STEp	3.22	19.53	0.51	1.29
YOL	3.74	37.02	0.57	1.57
BRAp	5.26	26.26	0.72	1.42
DAV	2.56	22.94	0.41	1.36
DEN	2.34	23.37	0.37	1.37
JAN	2.98	53.66	0.47	1.73
JOH	3.54	27.12	0.55	1.43
MAR	3.00	47.25	0.48	1.67
MAT	5.12	44.97	0.71	1.65
PET	11.51	76.93	1.06	1.89
CCD	2.87	32.32	0.46	1.51
CCQ	10.67	98.46	1.03	1.99
CHES	6.39	25.44	0.81	1.41
KIMM	6.81	38.16	0.83	1.58
MIK	2.19	64.82	0.34	1.81
NAT	9.48	39.44	0.98	1.60
STU	6.05	74.91	0.78	1.87
TRA	9.82	84.42	0.99	1.93
ANDp	7.81	27.16	0.89	1.43
ANG	7.97	38.49	0.90	1.59
DIA	3.15	28.56	0.50	1.46
JEA	8.99	50.22	0.95	1.70
Q	12.89	79.62	1.11	1.90
SCOp	8.30	29.38	0.92	1.47
SHA	10.05	45.31	1.00	1.66
STE	7.80	52.95	0.89	1.72
ALE	2.95	28.12	0.47	1.45
ELI	2.60	45.78	0.42	1.66
ING	1.73	25.36	0.24	1.40
JON	1.49	14.83	0.17	1.17
LIN	1.29	26.52	0.11	1.42
ROBp	1.41	29.20	0.15	1.47
SOH	2.22	40.60	0.35	1.61

SUS	1.43	22.25	0.16	1.35

Corrected for one Subject with extreme values in both tasks.

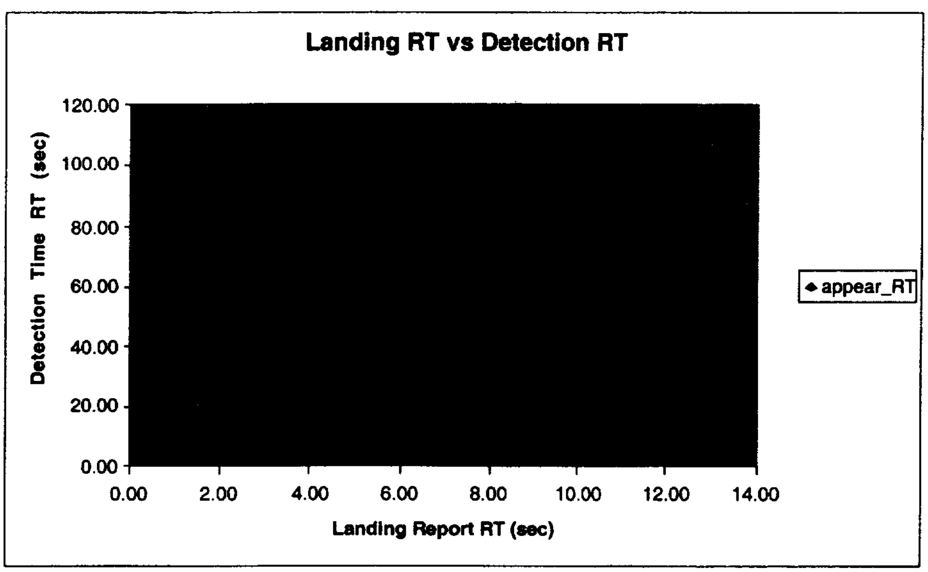
SUMMARY OUTPUT

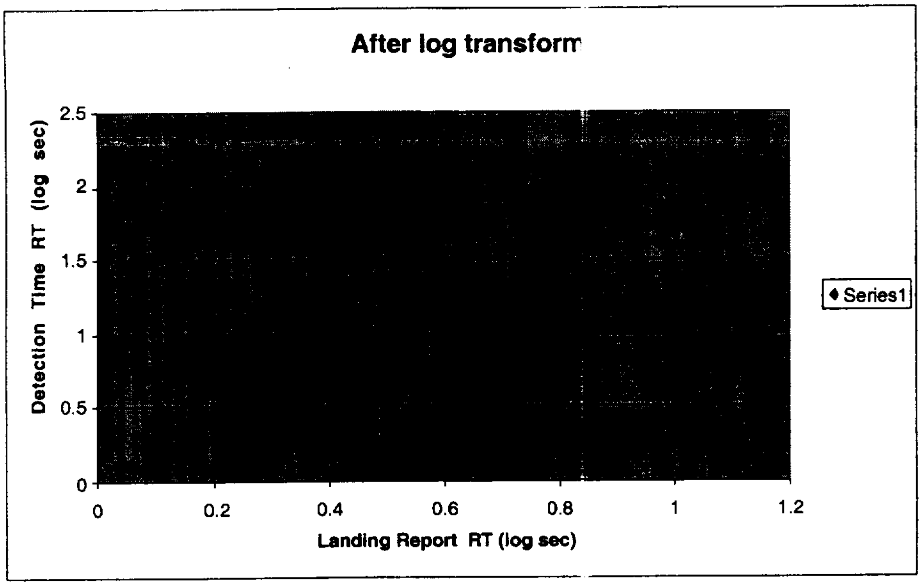
Regression Statistics	
Multiple R	0.6119796
R Square	0.37451903
Adjusted R Square	0.35848105
Standard Error	15.9035889
Observations	41

SUMMARY OUTPUT

Log transformed RT

Regression Statistics	
Multiple R	0.53602601
R Square	0.28732389
Adjusted R Square	0.26905014
Standard Error	0.16842073
Observations	41




After log transforr
Detection Time RT (log sec)
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1
1.2
Landing Report RT (log sec)
Series1

Appendix H: Chi² tests

appear

WFOV	MFOV	SFOV		Expected frequency	CHI² with no contingency corrections
3	6	18	27	5.882682	1.412596
8.7	9	9	26.7	7.541899	0.315233
11.7	15	27	53.7	13.57542	1.442086
				5.817318	1.428468
				7.458101	0.318775
				13.42458	1.458289
				CHISQR=	6.375446

CHI(2) krit:5.99

Land

WFOV	MFOV	SFOV		Expected frequency	CHI² with contingency correction
4	5	11	20	5.059873	0.06195
5.93	6.66	6.66	19.25	5.941401	0.032793
9.93	11.66	17.66	39.25	8.998726	0.25046
				4.870127	0.064363
				5.718599	0.03407
				8.661274	0.260218
				CHISQR=	0.703855

appear

	MFOV	SFOV		Exp.freq	CHI² with corrections
partial overlap	3	19	22	4.226852	0.12499
full overlap	5.3	15.9	21.2	17.77315	0.029725
	8.3	34.9	43.2	4.073148	0.129706
				17.12685	0.030847
				CHI2	0.315269

CHI(1) crit: 3.84

land

	MFOV	SFOV		Exp freq.	CHI² with corrections
				3.941722	0.049501
partial	3	13	16	12.05828	0.016181

overlap					
full overlap	4.44	9.76	14.2	3.498278	0.055775
	7.44	22.76	30.2	10.70172	0.018232
				CHi2	0.13969

Report Documentation Page

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Joelle R. Schmidt-Ott, Stephen R. Ellis, Bernard D. Adelstein, Jimmy Krozel, Ronald J. Reisman, and Jonathan Gips

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Ames Research Center
Moffett Field, California 94035-1000

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Point of Contact: Stephen R. Ellis, M/S 262-2, Ames Research Center, Moffett Field, CA 94035
(650) 604-6147

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13. ABSTRACT *(Maximum 200 words)*

An optical see-through, augmented reality display was used to study subjects' ability to detect aircraft maneuvering and landing at the Dallas Ft. Worth International airport in an ATC Tower simulation. Subjects monitored the traffic patterns as if from the airport's western control tower. Three binocular fields of view (14°, 28° and 47°) were studied in an independent groups' design to measure the degradation in detection performance associated with the visual field restrictions. In a second experiment the 14° and 28° fields were presented either with 46% binocular overlap or 100% overlap for separate groups. The near asymptotic results of the first experiment suggest that binocular fields of view much greater than 47% are unlikely to dramatically improve performance; and those of the second experiment suggest that partial binocular overlap is feasible for augmented reality displays such as may be used for ATC tower applications.

14. SUBJECT TERMS
Augmented reality, Head-mounted display, Low visibility visualization, Airport tower display

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